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RETRIEVING INFORMATION ABOUT LOCATIONS

James G. Greeno, Maria E. Magone,  
Alexander W. Siegel, and James J. Mokwa

University of Pittsburgh

January 26, 1981

Technical Report No. 6



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Retrieving Information about Locations

James G. Greeno, Maria E. Magone,  
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ABSTRACT

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In experiments measuring latencies to answer questions about relative locations, Lea (1975) supported a hypothesis that locations are represented in a list ordered according to adjacency relations, and Hintzman, O'Dell, and Arndt (1979) supported a hypothesis that distances and directions between objects are represented. We propose a hypothesis that locations are represented using a spatial schema, and that procedures for answering questions include processes that operate on positions in the spatial schema. We hypothesize further that different performance observed by Hintzman et al and Lea can be interpreted as a difference of retrieval procedures induced by differences in the ways that questions were presented. We conducted an experiment in which different questions were asked in different conditions about locations of objects, where the tasks were comparable in ways that Hintzman et al's task and Lea's task were not. Latencies in the two conditions differed in the same way as the earlier findings, lending support to the hypothesis of different retrieval procedures induced by differences in the question-answering tasks.

## Retrieving Information about Locations

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Characteristics of information retrieval depend jointly on the way in which information is represented in memory and the process used to search for information. In this study, we investigated alternative forms of questions about the locations of objects, hypothesizing that the different questions would induce subjects to use different retrieval processes, or to represent information about locations differently, or both.

Results of two recent studies have provided evidence of quite different processes of retrieval with similar materials. Hintzman, O'Dell and Arndt (1979) and Lea (1975) had subjects memorize locations of objects located around the perimeter of a closed figure. In Lea's display objects were pictured on an approximately circular path, while Hintzman et al showed drawings in eight positions around a room or on the edges of an octagon.

Hintzman et al (1979) and Lea (1975) both measured latency to retrieve information about locations of objects, but their question-answering tasks were quite different. In Hintzman's task, one of the line drawings was presented on a crt display for two sec with the instruction, "Face this object," than another of the drawings appeared with the instruction, "Locate this object." The subject had a response board with eight copper arcs arranged in a ring. The task was to imagine being located in the center

of the display, oriented facing the first object, and then move a stylus from the center of the ring in the direction the second object would be from that orientation.

In Lea's (1975) task, a subject was shown the name of one of the objects and a numeral. The task was to remember where the named object was in the display, then report which object was located in the position clockwise from the named object the number of positions equal to the presented numeral.

Data from the two studies are shown in Figures 1 and 2. Note that in Lea's data, shown in Figure 1, latency was an approximately linear function of the numeral that was in the question. Lea's interpretation was that subjects represented locations in a circular list, whose order corresponded to the order of the objects around the perimeter of the display figure. According to Lea's model, the subject first entered the list at the named object and then incremented the list a number of times equal to the presented numeral, reporting the name of the object reached by the last increment.

Hintzman et al's data, in Figure 2, clearly require a different interpretation. The interpretation favored by Hintzman et al involves a representation that includes relational memory codes. According to this model, subjects stored relationships between the locations of pairs of objects, in the form "Y is D degrees away from X, in direction S," where D is an angular distance, and S is right, left, or opposite. The empirical findings are explained by assuming that codes involving distances of  $45^{\circ}$  or opposite directions are strong, leading to faster responding, and that  $90^{\circ}$  codes, and especially  $135^{\circ}$  codes, are weaker.

An alternative model that Hintzman et al did not consider assumes that locations are represented in relation to positions in a spatial frame, rather than in relation to each other. In this model, directions and distances

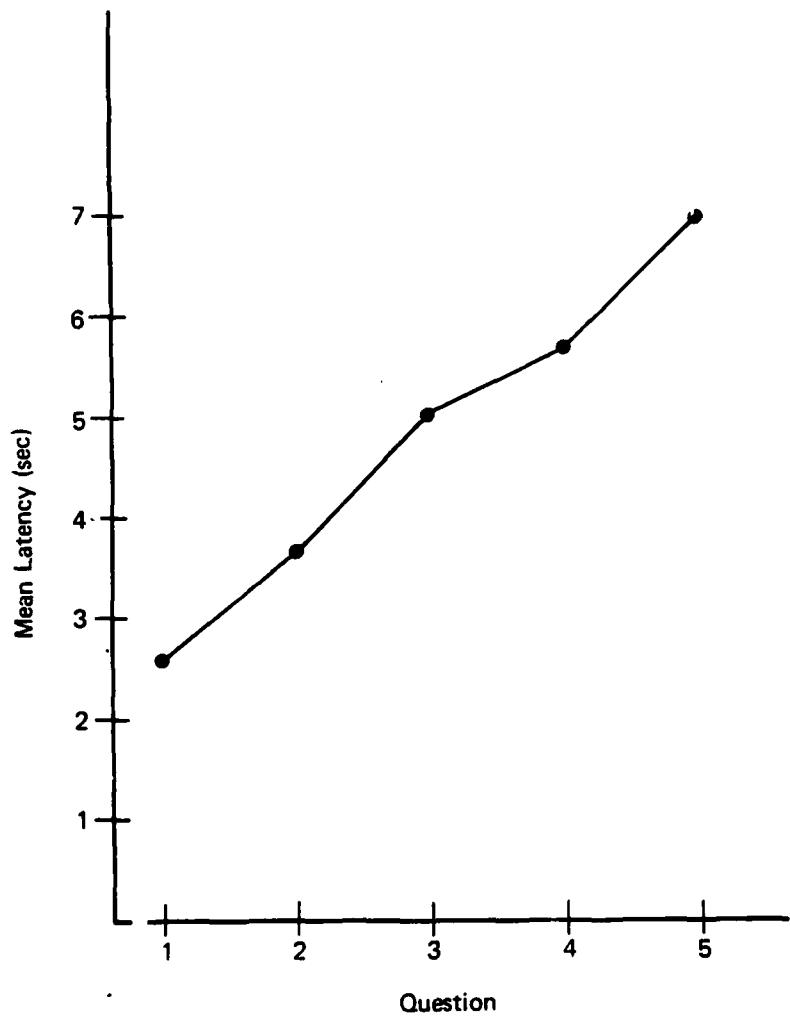


Figure 1. Latencies Obtained in Lea's Experiment 3 as a function of the number of positions from the referent object to the answer.

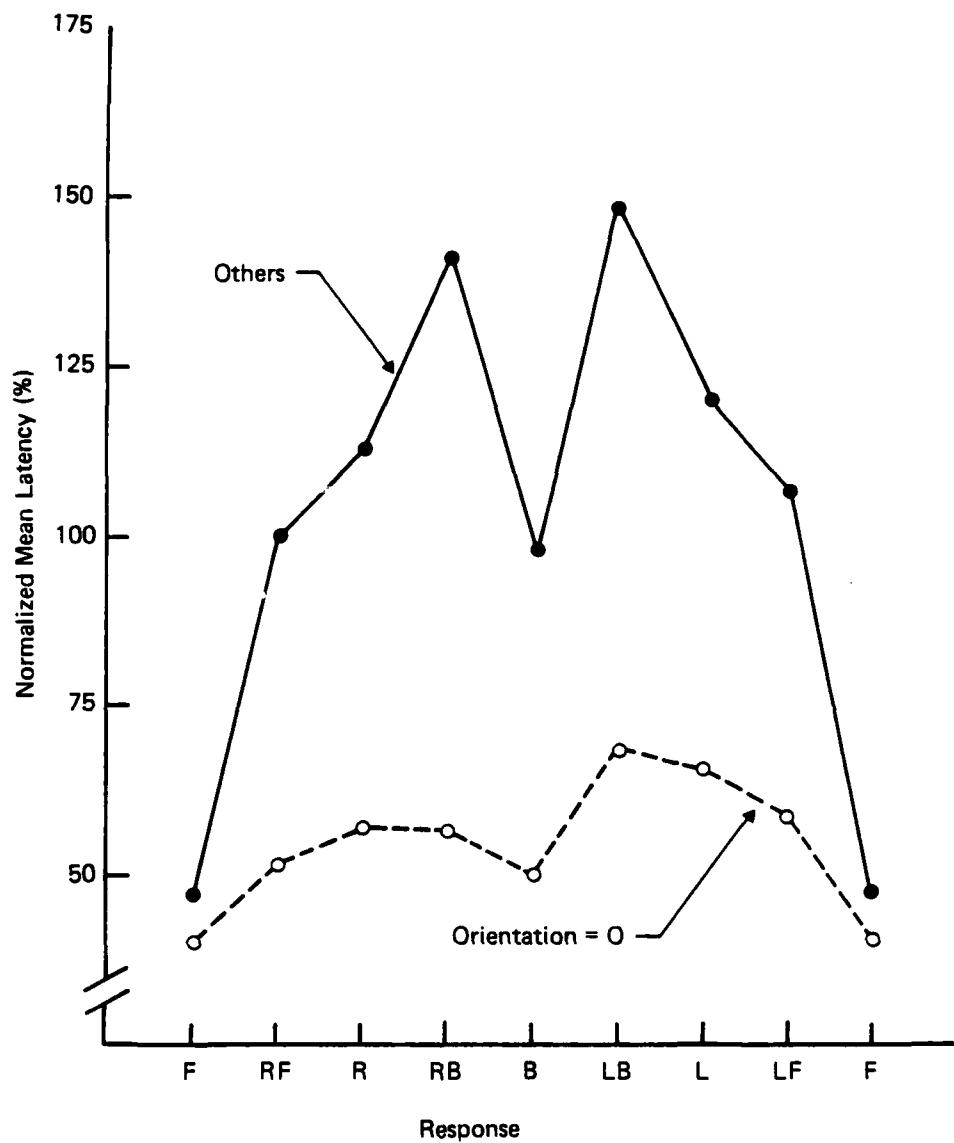


Figure 2. Latencies obtained in Hintzman's Experiment 5. Responses were F = front, RF = right front, R = right, RB = right back, etc. Orientation = O is the referent figure that was at the top of the display studied by students.

between objects would be inferred by a computational process, rather than stored directly as data. For eight items pictured on a vertical display, it would be natural to identify the positions as top, upper right, right, lower right, bottom, etc. The plausibility of this kind of representation is strongly supported by Rock's (1973) studies of recognition of forms after changes in their orientation. Rock found more interference with recognition when a form's orientation in a frame was altered than from other changes, such as changing its orientation on the viewer's retina. He concluded that the cognitive representation of a form is analogous to a description in which the various features have locations such as "top," "bottom," and "lower left corner." This kind of representation also is consistent with Hintzman et al's (1979) finding, illustrated in Figure 1, of shorter latencies when the first object named in the question was at the top of the array that the subject had studied; these latencies are on the function labeled "orientation = 0."

We also assume that general procedures are available that operate on the contents of the spatial frame. We assume that these general procedures are analogous to those that can be used in scanning a visual display. The procedures that would be relevant in Hintzman et al's task are used in computing distances and directions between two positions in the frame. For example, if there are eight items equally distributed on a circular display and the pair of positions "upper right, left," is given, then the procedure that we hypothesize returns the value "move left, three positions." Given the positions, "upper left, lower right," the procedure returns "opposite." According to our introspections, we can make computations like this, and we think we use visual imagery in doing so, much as we scan a visual display. However, the question whether a visual image is required for such a procedure is not one that we intend to address in this report (cf. Anderson, 1978).

In our model, Hintzman et al's result is explained by assuming different amounts of difficulty in performing the computations required to answer different questions. We assume that presentation of the two objects activates the frame positions corresponding to the objects' locations, the direction and distance from the first to the second object are computed, and a response is generated by computing the same direction-distance pair from the front position on the response board. The increased time needed for displacements one, two, and three positions (either to the right or the left) is explained by assuming that distance computation takes longer when the separation between positions is greater. The much shorter latency for the displacement of four positions is explained by the ad hoc (but plausible) assumption that computing the "opposite" result is especially easy.

It is not surprising that our model can explain the same findings as Hintzman et al's can. The models are identical except for a procedure-memory tradeoff. In our model, there is computation of relations between positions that are stored in memory according to Hintzman et al's interpretation. The variations in complexity of computations in our model correspond to the variations in strength of memory codes in theirs.

Lea's results also can be interpreted using the idea of representation in a spatial frame. Assume again that the objects are associated with the positions of a spatial frame. When an object is named, its position is activated. Then a numeral is presented and the subject computes a second position displaced clockwise from the first position by that number of entries in the frame. Finally, the subject reports the object that is associated with the position that was returned by the procedure. Our model for Lea's task also is completely compatible with Lea's own interpretation. The computation of the required position involves traversing positions in the

spatial frame, where his model involves incrementing a list the same number of times.

Our models for Hintzman et al's and Lea's tasks share a representation of locative information, but differ in the procedure used for finding answers to questions. For Hintzman et al's task, the procedure has inputs consisting of two positions and computes the direction and distance between the positions. For Lea's task the input is a position and a distance (the direction is constant), and the output is a second position. In principle, the two procedures could be inverse functions. The data say they are not, because if they were, one would expect their complexity to be comparable in both directions. In the experiment that we report below, we compared Lea's task with a task that we hypothesize requires the inverse computation of the procedure that we have postulated for Hintzman et al's task, and found that the latencies for that task were similar to those obtained by Hintzman et al.

We hypothesize that subjects were induced to use different retrieval procedures in Hintzman et al's and Lea's experiments because of differences between the question-answering tasks. Lea's questions used numerals, whose serial structure maps directly into a retrieval procedure that uses a simple ordering of objects in memory. Hintzman et al's task required directional responses, and the properties of the response alternatives are easy to map into a richer set of spatial relationships such as right and left directions and opposite positions across the array. Our experiment was designed to encourage the same kind of difference between retrieval processes that we hypothesize to explain the difference between Lea's and Hintzman et al's latency functions. However, both of the tasks we used involve presenting a question with the name of one object along with a cue, and answers involve naming a second object. Thus, both tasks require retrieval of information

in the same cognitive direction. According to our model, the computational procedures for both tasks receive input that includes a position, along with other arguments, and return another position as output.

Both of our experimental tasks involved retrieving information about locations of eight objects placed around the perimeter of a circle at equal distances. One task was patterned after Lea's. Each question in this condition presented the name of an object and a numeral, and the correct answer was the name of the object located the number of positions clockwise from the named object equal to the numeral. We hypothesized that performance in this task would be essentially like that observed by Lea, although we expected the latency function to decrease for question with larger numerals (7, and perhaps also 6) because we thought subjects would not have to count all the way around to find the position(s) just counter-clockwise from the named object.

In the other task that we used, each question presented the name of an object and a compass direction: S, SW, W, NW, N, NE, E, or SE. The answer could be found by placing an imaginary compass dial on the circular array of objects with S on the named object, then locating the position of the named compass point and naming the object at that location. We hypothesized that this task might induce a process of retrieval that would use more of the spatial relations in the display than the adjacency relations that Lea's task seems to require. In particular, we expected that the relation of being opposite across the array would be easy to compute, causing the answers to N questions to be answered quickly. Some further ideas about the computational process involving perpendicular vectors also led us to expect that questions involving E and W might also be relatively easy compared with questions involving the diagonal directions, at least for some subjects.

We cannot guarantee, of course, that subjects in these two conditions represented information about locations in identical ways. However, all subjects were run in both conditions, with the order balanced. If significant differences in representation occurred, they might cause a substantial interaction between order and other experimental variables.

#### METHOD

##### Subjects and Designs

The subjects were eight male and eight female undergraduate students who participated to fulfill a requirement of the introductory psychology course. Each subject participated in two sessions, separated by approximately seven days. One-half of the men and one-half of the women were in the compass-direction condition in their first session and the numeral condition in their second session, and the other subjects had numerals first and directions second. In each session subjects were given instructions about the kind of questions they would have to answer, memorized the locations of the eight objects, and answered two blocks of 64 questions. Each block of questions included all the combinations of eight objects combined with eight numerals (0 - 7) or eight compass directions.

##### Procedure

All subjects were shown materials displayed in the same way. A white cardboard circle, 46 cm in diameter, was shown with rectangular pictures of objects located as shown in Figure 3. The pictures were colored photographic reproductions of drawings of the objects, 6 cm by 8.5 cm in size, which were chosen primarily for having simple names. The objects were in the order shown in Figure 3, but they were rotated to different positions from subject

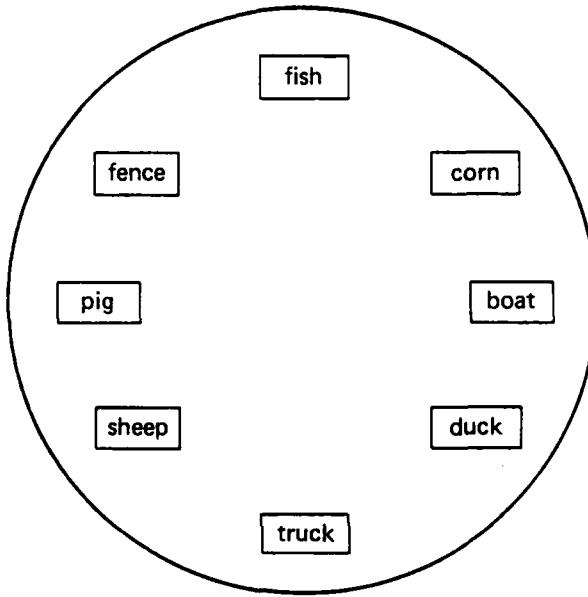


Figure 3. Display card with one arrangement of objects. (Stimuli used were pictures, not words.)

to subject. The display card had black rectangles permanently fastened in the positions of the pictures, and this card was used to test subjects' knowledge of the locations after they studied the display with the pictures.

Instructions for memorizing the locations were different for subjects in the two conditions.<sup>2</sup> When questions were to involve compass directions, subjects were shown another cardboard circle, the same size as the display card, which showed the eight compass directions placed around its perimeter. The subject was told that each question would consist of the name of an object and a compass direction. The subject was to study the display until it was possible to answer questions without the pictures. This involved locating the position of the named object, then mentally superimposing the compass over the display card, with S pointing to the named object. This operation would produce an association between each picture and one of the compass directions. The subject should then identify the location of the direction point mentioned in the question, and report the name of the object located there.<sup>3</sup> Some examples were given. For example, in Figure 3, if the question was "Duck W", the suggested procedure involved recalling the position of the picture of the duck, then thinking of the question, "If duck is at south, what is at west?" The answer would be Sheep. If the question was "Corn NE," the subject should recall the position of the picture of corn, mentally place the compass on the display with S at that picture, and report which object was located at northeast, i.e., the fence. The subject was given time to study the locations and practice the procedure until the subject could confidently answer any question involving an object and a direction.

When questions were to consist of objects and numerals, subjects were not shown the compass. Each subject was instructed with the display card until, with the objects taken away, the subject could name all the objects in order

around the circle, starting with any object named by the experimenter. When the subject met this requirement, questions were presented consisting of an object and a numeral. Then the subject was to locate the position of the named object, count clockwise the number of positions equal to the numeral in the question, and report which object was located at the position. For example, in Figure 3, for "Truck 4," the subject recalled the position of the truck, counted four rectangles clockwise, and reported which object was at that position, i.e., Fish. The subject studied and practiced until any object-numeral question could be answered confidently.

During the two blocks of questions the subject and experimenter sat back-to-back, each facing a video terminal. In both conditions, subjects could see, but not touch, the display card without pictures. In the compass-direction condition, subjects could also see the circular card with compass directions. On each trial, the subject pushed the space bar at the subject's terminal. This started a timer and caused a question to appear on both the subject and the experimenter's screens, and the correct response also appeared on the experimenter's screen. The subject responded by speaking the name of an object into a microphone connected to a voice-operated relay which stopped the timer. The experimenter typed a response code indicating whether the subject had given the response. At the end of a session, questions that had been answered incorrectly were repeated, so that latencies for a complete set of correct responses were collected.

## RESULTS

### Analyses of Mean Latencies

Figure 4 shows the mean latencies for the eight types of question for the two conditions. Data for each question type were averaged over the eight

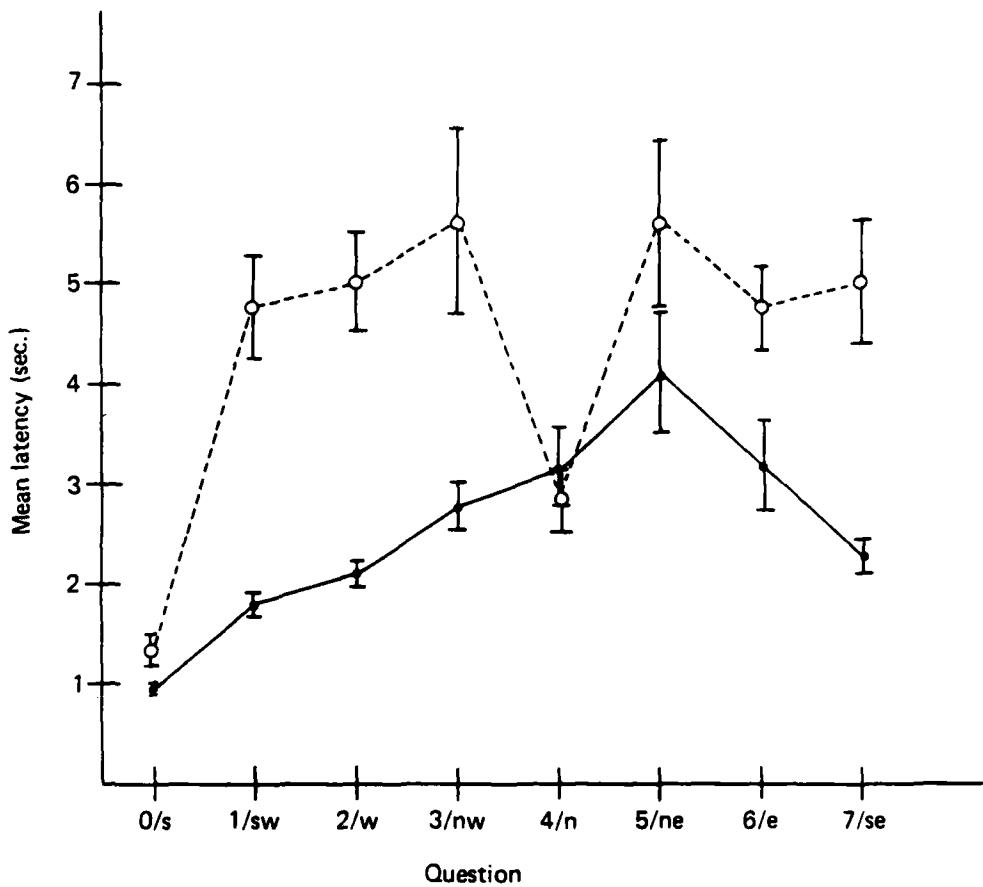


Figure 4. Mean latencies for all subjects. Open circles are data from the compass-direction condition; closed circles are from the numeral condition.

positions of the reference objects. There are two obvious findings in the data. First, the expected relative ease of questions involving N in the compass-direction condition apparently was obtained. Second, and not expected, the latencies were generally longer when retrieval was cued by compass directions than when it was cued by numerals.

Confidence intervals were computed to assess reliability of findings. For the difference between latencies in the two conditions, the difference in average latency for all 128 correct responses in each condition was calculated, and the difference between the two values was found. The mean of these difference scores was 1.82 sec. The estimated standard deviation of these difference scores was used to calculate a confidence interval: with 95% confidence,  $(0.81 < \mu_d < 2.83)$ ; since the interval did not include zero, the difference is significant at the .05 level.

Regarding the apparently shorter latency for N questions in the compass-direction condition, the question of greatest interest is whether the average effect was different in the two question conditions. To assess this, we calculated the difference between each subject's average latency for N questions and the average for the remaining questions, (Latencies for the S question were omitted.) Thus, the score calculated for each subject was

$$\frac{SW + W + NW + NE + E + SE}{6} - N.$$

The corresponding score was also calculated for the numeral questions, with the latency for question 4 subtracted from the average of questions 1, 2, 3, 5, 6, and 7. The difference between these two scores was calculated for each subject and a confidence interval was estimated. The hypothesis of a greater relative advantage for N in the direction condition than for 4 in the numeral condition predicts that the score for the direction questions should

be significantly larger than the score for the numeral questions. The average of the difference scores was 2.71. A 95% confidence interval was estimated in the same way as described earlier. It was ( $1.86 < \mu_d < 3.57$ ), so the result was clearly significant.

Practice and order of the conditions did not interact significantly with the main effects. Data were examined to assess possible interaction between practice and the two main effects described above. First, there was a trend toward faster responding in the second session. Averaging across both conditions, the average latency in the first session was 3.78 sec, compared to 3.16 sec in the second session. This may have produced an interaction between the difference between conditions and the order of conditions. The average difference between directions and numerals was larger by 1.25 sec for subjects who had directions first, but the 95% confidence interval was ( $0.71 < \mu_d < 3.21$ ), indicating that the interaction was not reliable.

Another possible interaction would involve unequal practice effects due to order. Subjects who had numerals first had a mean latency of 3.04 sec with numerals and 4.23 sec with directions. Subjects who had compass directions first had a mean latency of 4.53 sec with directions and 2.08 sec with numerals. The suggestion that directions helped numerals more than numerals helped directions was not borne out by the statistics. The measure is the difference between the order groups' sums of mean latencies across the two question conditions, and it was not significantly different; with 95% confidence, ( $-2.08 < \mu_d < 3.76$ ).

A final interaction that was examined involved the amount of advantage for N and 4 vs. the other questions. For example, if subjects who received compass directions first became accustomed to using the opposite positions

in retrieval, their latencies might have a dip at 4 when they answered questions with numerals that might not appear in the data of subjects who had numerals first. This would appear as a smaller dip effect (directions minus numerals) for the group with directions first. The scores measuring the dip at N vs. the dip at 4 were used, comparing the average difference between the two order groups. The difference was not significant; with 95% confidence,  $(-1.26 < \mu_d < 2.24)$ .

#### Analyses of Individual Subjects' Latency Patterns

If we take the dip in latency at N as evidence that the process of retrieval used information about opposites, then the greater dip in data from direction questions indicates a greater average tendency for such information to be used with those questions than with questions in which numerals were used. We performed a further analysis to obtain information about possible systematic differences between individual subjects. The possibility that interested us is that different subjects might show substantially different patterns of latency, suggesting systematic differences in use of spatial information in their retrieval processes.

The strategy we used involved a technique for identifying dips at E, N, and W (and 2, 4, and 6). We analyzed latencies of each subject's responses in each of the four blocks of trials. For each block of 64 trials, a simple one-way analysis of variance was performed to estimate the variance of responses for repetitions of the same question type. The conditions of the analysis of variance were the different question types, and the within-condition mean square was taken as an estimate of  $\sigma^2$ .

The following contrasts were examined:

$$C_2 = \frac{\bar{x}_1 + \bar{x}_3}{2} - \bar{x}_2,$$

$$C_4 = \frac{\bar{x}_3 + \bar{x}_5}{2} - \bar{x}_4,$$

$$C_6 = \frac{\bar{x}_5 + \bar{x}_7}{2} - \bar{x}_6,$$

$C_2$  measures a dip at question W or 2,  $C_4$  measures a dip at N or 4, and  $C_6$  measures a dip at question E or 6. (Note that the contrasts are not independent.  $C_2$  and  $C_4$  are positively correlated, as are  $C_4$  and  $C_6$ .) A positive value of  $C_i$  means that  $\bar{x}_i$  is smaller than the average of the average of the two adjacent mean latencies. In other words, a positive  $C_i$  means that  $\bar{x}_i$  was below a straight line connecting  $\bar{x}_{i-1}$  and  $\bar{x}_{i+1}$ . We identified a dip in a function when the relevant contrast was positive and was larger than the standard error of the contrast. The standard error of each contrast is

$$SE(C_i) = \sqrt{\frac{3}{16} \sigma^2}.$$

(Each  $\bar{x}_j$  is based on eight observations, thus,

$$SE(C_i) = \sqrt{\frac{\sigma^2/8 + \sigma^2/8}{4} + \sigma^2/8.}$$

This analysis provided a classification of each block of trials into one of eight categories consisting of the combinations of presence or absence of a dip in each of three locations that were examined. The frequencies of these patterns in the two retrieval conditions are shown in Table 1. For example, the pattern 010 has a dip at N or 4, but not at W or E (2 or 6). This occurred frequently in both conditions. However, when

Table 1

Frequencies of Patterns of "Dips"  
in Latency Functions

	000	001	010	100	011	101	110	111
Numerals	13	3	9	0	3	0	3	1
Compass Directions	1	0	17	1	4	0	4	5

retrieval was cued with numerals, most of the remaining blocks had no dips, while in the direction condition 13 blocks had either two or three dips.

A statistical test based on Table 1 would be inappropriate due to non-independence of observations. However, the difference between conditions can be tested by comparing the number of dips identified in each subject's performance in the two conditions. For each subject, the number of dips in the two numeral blocks was subtracted from the number in the two direction blocks. The mean of these differences was 1.38; with 95% confidence, ( $0.20 < \mu_d < 2.56$ ), hence, the difference was significant at the .05 level. This measure of patterning was not significantly affected by practice. The difference between numbers of dips in the direction vs. the numeral conditions did not differ depending on which condition was presented first (95% CI:  $-2.03 < \mu_d < 2.86$ ).

We examined graphs of latencies for individual subjects, but they seemed too irregular to permit interpretation. It seemed useful, however, to combine relatively homogeneous sets of data and look at the patterns that were present. We formed sets of data based on the statistical identification of latency-function dips. Figure 5 shows the mean latencies for 16 subject-blocks in the numeral condition where there either were no dips or a single dip at question 6. The pattern is just the one we expected for the numeral questions: monotonically increasing latencies through most of the function, turning down at questions 6 and 7. Since there were only two subject-blocks in the direction condition with no dips or a single dip at either E or W, a comparison of the data in Figure 5 with the direction condition is not possible.

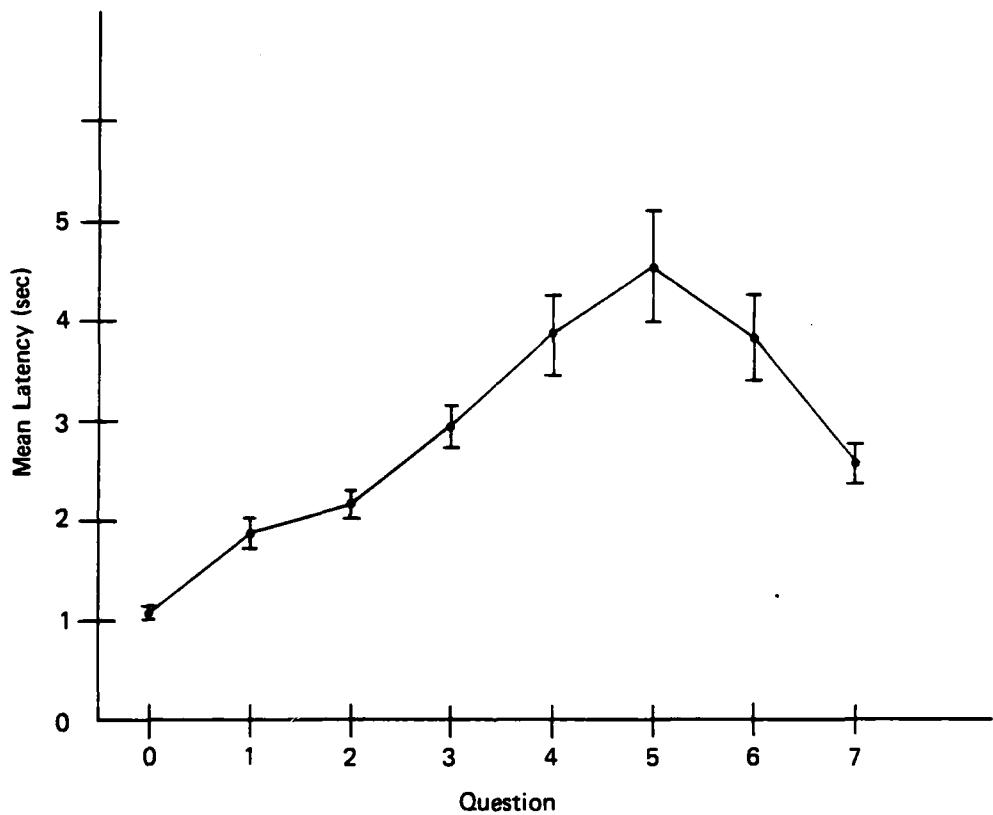


Figure 5. Latencies for subject blocks with no dips or one dip at 4.  
(Numerals: 16 subject-blocks)

Figure 6 shows mean latencies for subject-blocks with a single dip at N or 4. There were nine such subject-blocks in the numeral condition and 17 in the direction condition. The data from the direction condition matches closely the pattern we initially hypothesized for the these questions. One could infer relatively direct access to the locations just adjacent to or directly opposite from the object named in the question, with some further computation or memory search needed for any other location. The pattern from the numeral condition is characterized mainly by the uniformly short latencies. Perhaps in these blocks subjects had quite thorough knwoledge of the locations in the array, including knowledge of numerous distances between objects permitting direct retrieval, with a somewhat greater tendency to know directly about opposites and directly adjacent pairs than other relationships.

Figure 7 shows the mean latencies from subject-blocks with two or three dips. Comparing Figure 7 with Figure 6 the additional irregularities at W and E seem caused more by longer latencies at the neighboring points in Figure 7 than by shorter latencies at W and E. This suggests that the pattern in Figure 7 might result from fairly rapid access to the opposites, somewhat less knowledge about the locations on perpendicular axes, and relatively poor knowledge about the diagonal locations. The pattern in Figure 6 could involve similar knowledge about opposites and perpendicularly, with added knowledge about the diagonals, especially those diagonal locations between the opposites and perpendicularly. We think this hypothesis probably is partially accurate, but it has an implication that shows it is not the whole story. If it were generally correct, the pattern in Figure 6 should typically have been obtained in sessions following the pattern in Figure 7, but we obtained no evidence for such a practice effect. (Five subjects

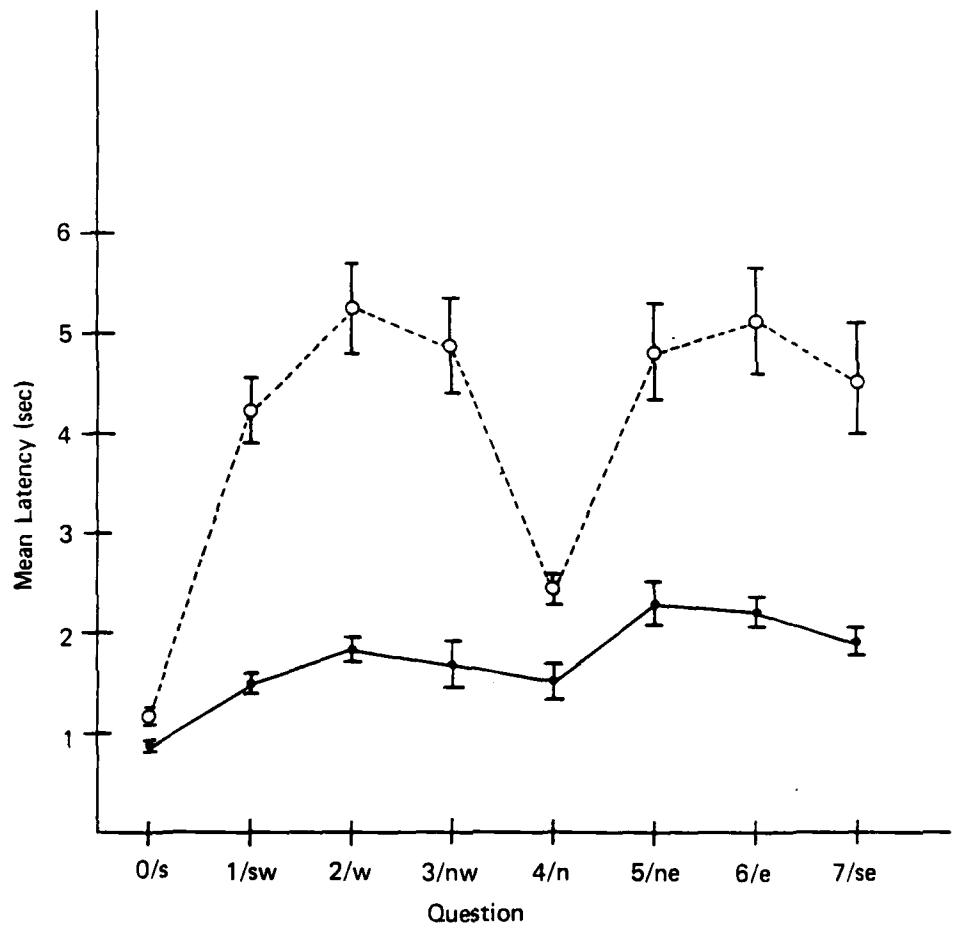


Figure 6. Latencies for subjects with one "dip" at 4 or n.  
(Numerals: 9 subjects-blocks; Directions: 17 subjects-blocks)

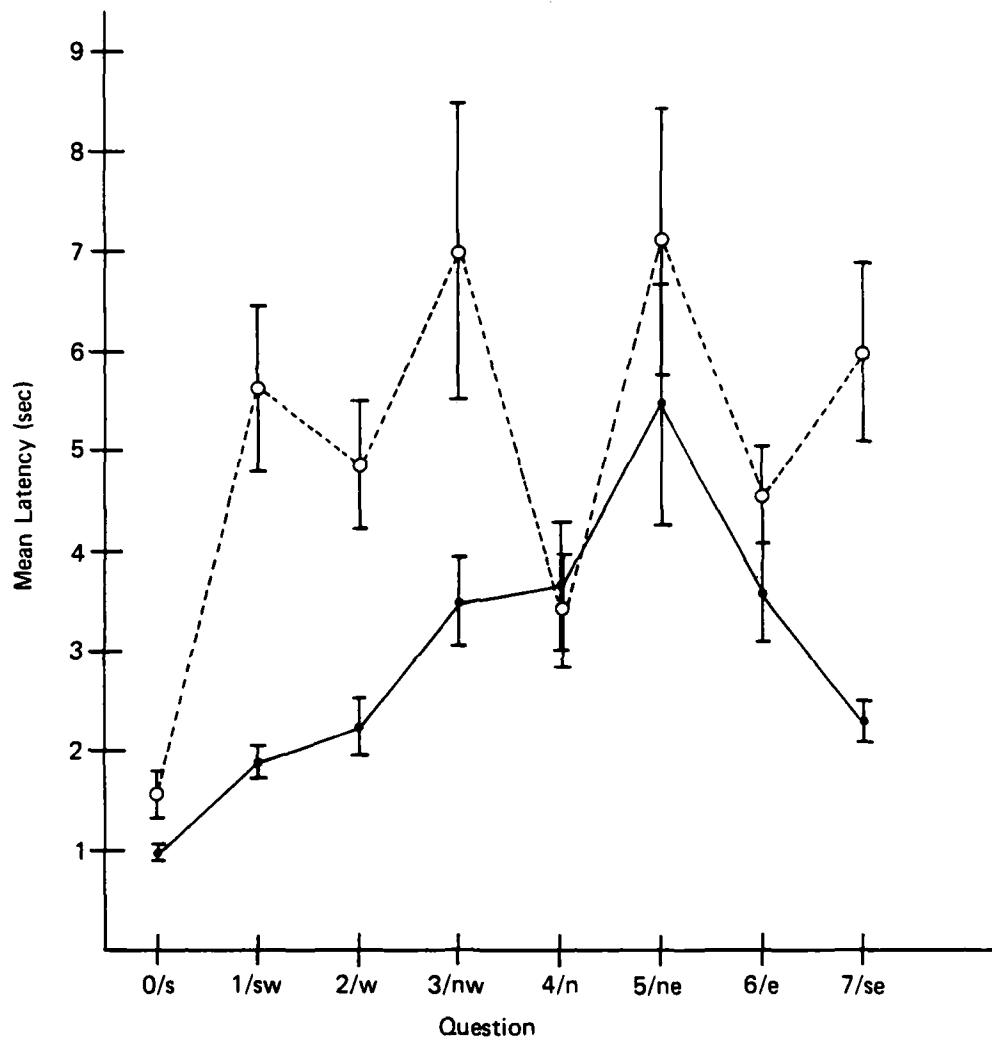


Figure 7. Latencies for subjects with two or three significant "dips."  
(Numerals: 7 subject-blocks; Directions: 13 subject-blocks)

were in Figure 6 on both of their blocks, and four were in Figure 7 in both blocks. Of subjects who switched patterns, three switched from Figure 6 to Figure 7, and two switched from Figure 7 to Figure 6.)

The pattern in Figure 7 from the numeral condition has much less striking irregularities. (Note from Table 1 that only one of the seven subject-blocks represented here had statistically identified dips at all three locations, while five of the direction-condition blocks had three dips.) The pattern in Figure 7 is quite similar to the pattern in Figure 5 both in overall shape and overall average latency. It seems plausible to conclude that the dips in the latency functions in the numeral conditions were usually caused by some incidental local knowledge, whereas it seems more likely that the dips found in the direction condition were produced somewhat more systematically.

#### DISCUSSION

In this concluding section we extend the discussion of the introduction regarding representations and retrieval procedures, partly based on some informal interviews we conducted with two subjects who gave retrospective protocols as they worked on the question-answering task involving directional cues.

As we stated in the introduction, we believe that the basic representation of information about locations involves associations between objects (or their names) and slots in a spatial schema. The main anchors are the top, bottom, right, and left positions, and other objects are probably located in relation to those positions.<sup>4</sup> We also assume that there are computational procedures that operate on spatial positions that can find new positions in relation

to positions that are given, or that can find relations between pairs of positions.

We interpret the results of our experiment as a difference of characteristics of information retrieval that were influenced by the way in which questions are asked. The lack of significant interactions between the order of conditions and other variables is consistent with this interpretation. While we cannot be sure that subjects' representations in the two conditions were identical. The differences in latency patterns can be explained by assuming that in both conditions, subjects represented the locations by associating objects with their positions in a spatial frame, but were induced to use different computational procedures to retrieve answers to questions. According to this interpretation, in the numeral condition subjects entered the spatial array at the position of the named object and computed the position corresponding to the numeral that was presented, either by counting clockwise, or retrieving the adjacent (or adjacent-but-one) position in the counter-clockwise direction. In the direction condition, other spatial relationships were used in the computation--especially the opposite relation, but also, for some subjects, relations involving the diameter perpendicular to the one that pointed to the named object.

This view is technically adequate to explain our results. However, we believe that it is incomplete, partly because of some supplementary data that we collected from two subjects who performed the direction-question task after only a small amount of study of the display. These subjects were asked occasionally in the session to describe the way in which they answered questions. Their retrospections indicated that their representations were growing as a result of their practice in the task. Part of that growth involved knowledge of where things were. Early in the task there was

uncertainty about which positions held certain objects, and vice versa, but those associations were firmer as subjects worked on the task. Another part of the growth involved addition of relationships to the data base, especially involving objects not on the vertical or horizontal axes of the display. Relationships that had to be computed early in practice could be retrieved directly after some experience.

It is not hard to account for the development of directly retrievable relationships if we assume that our model describes the process used initially, and that a standard learning mechanism is operating. Results of computations can be stored in a number of ways, including composition of productions. (Given a certain input, and a result of computation on that input, form a production that returns the result directly when that input is present--cf. Larkin, in press; Lewis, 1978.) If we allow for the addition of relations that can be retrieved directly, the model we have proposed becomes even harder to distinguish from those of Hintzman et al (1979) and Lea (1975). Recall that our model differs from theirs mainly in the assumption that certain items of information were inferred as a result of computation in our model, while they were directly retrieved in theirs.

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## FOOTNOTES

<sup>1</sup>Now at the University of Houston.

<sup>2</sup>Before conducting this experiment, we conducted another one in which subjects were all instructed in the same way. Results of that study were very similar to those we report here, so we infer that the difference in instruction did not have a very strong influence.

<sup>3</sup>An alternative form of instructing subjects was tried, and led to such extreme difficulty that we abandoned it. In our initial method, subjects were asked to imagine rotating the array of objects so the named object was at the bottom--i.e., the S point of the compass. We hypothesize that the extreme difficulty our subjects had in learning the array under those conditions was due to interference with use of a stable spatial frame where one of the objects stayed at the top, another at the bottom, and so on.

<sup>4</sup>We are painfully aware that in addition to the evidence mentioned in the introduction, there should have been further evidence on this point from our study. Unfortunately, our experimental records did not include the orientation of the display presented to each subject, so we cannot recover the data needed to correlate performance with the positions of objects in the array that was studied.

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